DO SUBCONCUSSIVE IMPACTS CAUSE BALANCE DEFICITS IN ATHLETES?

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A thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Arts in the Department of Exercise and Sport Science (Athletic Training) in the College of Arts & Sciences

Chapel Hill
2020

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ABSTRACT

Matthew Booth: Do subconcussive impacts cause balance deficits in athletes?
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We systematically identified the effects of acute and cumulative subconcussive head impact exposure on balance in athletes. We searched eleven indexed scientific databases for articles pertaining to subconcussive impacts and outcomes related to balance. Eligible articles were reviewed and evaluated with three quality assessment tools. Articles (n=26,117) were screened and 21 met inclusion criteria. Articles demonstrated no conclusive evidence that balance/postural control is affected following acute and cumulative head impact exposure. We concluded the following given the reviewed evidence: 1) Balance/postural deficits are not seen following acute HIE but may be apparent following single-season exposure in collision, 2) generally low budget tests such as the BESS are similar to tests with advanced metrics, which is beneficial for clinicians who do not have the resources necessary for force plates and 3) consistent experimental protocols should be developed based on each balance/postural control outcome measure to allow for greater generalizability of results.

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LIST OF ABBREVIATIONS

ABC	Activities-Specific Balance Confidence
ANAM	Automated Neuropsychological Assessment Metrics
BESS	Balance Error Scoring System
CNS	Central Nervous System
D&B	Downs and Black Checklist for Quality Appraisal
DGI	Dynamic Gait Index
DHI	Dizziness Handicap Inventory
FGA	Functional Gait Assessment
GSC	Graded Symtom Checklist
GVS	Galvanic Vestibular Stimulation
HIE	Head Impact Exposure
HIT	Head Impact Telemetry
MRI	Magnetic Resonance Imaging
NFL	National Football League
NPRS	Numeric Perceived Rating Scale
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta Analysis
SET	Stability Evaluation Test
SIGN	Scottish Intercollegiate Guidelines Network
SOT	Sensory Organization Test
SST	Subconcussion-Specific Tool
SVQ	Situational Vertigo Questionaire
VOR	Vestibulocular Reflex

VSR	Vestibulospinal Reflex
YBT-LQ	Lower Quarter Y-Balance Test

CHAPTER 1

INTRODUCTION

Sport-related concussions are a highly researched and debated topic that affects a wide variety of athletes participating in many sports. Concussions can occur when biomechanical forces are transmitted to the brain via direct or indirect forces causing neurophysiological changes that can be observed via clinically relevant symptoms.[1] While concussive head impacts are concerning, most impacts sustained by athletes who participate in contact based sports are subconcussive. Collegiate football players can receive up to 950 subconcussive head impacts each season.[2] It is currently unknown how subconcussive head impacts affect the athletes in both the short and long-term timelines.

The literature has not been able to establish an exact threshold for a concussion to occur, due to brain dynamics during head impact being very difficult to understand.[2] Head impacts can cause translational or rotational acceleration, rapid change in rotational acceleration has also been shown to increase the likelihood of causing a concussive episode.[3] Subconcussive head impacts can cause quantifiable deformation in brain tissue, without the patient exhibiting any clinically observable symptoms that can be associated with a concussion.[4] Depending on the sport that you play and the position can determine the sheer magnitude and number of subconcussive impacts that you may receive over the course of a season.[5]

The vestibular system detects and receives information from the central and peripheral nervous systems so as to maintain balance and spatial awareness.[6] Tests such as the Sensory Organization Test (SOT) and the Balance Error Scoring System (BESS) assess vestibular function in athletes.[7] Whether or not the sheer number of cumulative subconcussive impacts can cause balance deficits has yet to be determined. This may be because outcome measures that are currently used to assess balance/postural control in athletes lack sensitivity to detect deficits. Researchers have not been able to determine the level of magnitude that a subconcussive impact needs to reach to cause neurophysiological damage to the brain. In order to make evidence-based clinical decisions, clinicians must first understand how subconcussive impacts affect balance/postural control. This will allow clinicians to provide the best evidence based care to prevent long-term deterioration of neurocognitive and balance/postural control.

The purpose of this systematic review is to determine what is currently known regarding the effect of subconcussive head impacts on balance in athletes. A comprehensive understanding of balance function following head impact exposure will add to the growing body of literature surrounding the short- and long-term affects of subconcussive head impacts, and help improve sport safety and long-term health.

Research Questions

1. Is cumulative subconcussive head impact exposure associated with balance changes in athletes?
2. Do dynamic outcome measures better detect balance changes following subconcussive impacts in athletes?

Research Hypotheses

1. The accumulation of subconcussive head impacts by athletes will cause balance deficits.
2. Dynamic measures of balance will be affected at a higher degree than static measures of balance.

Clinical Significance

Subconcussive impacts occur in a variety of different sports, the short-term effects of which are unclear. Cumulative subconcussive impacts over the course of a season may be causing balance deficits to athletes. For clinicians to provide the best medical care for their patients, subconcussive impacts and their affects on postural control must be better understood so that evidence-based decisions can be made. This will allow clinicians to make decision based on a multifaceted approach that includes information regarding symptom reporting, cognitive assessment and balance/postural control.

CHAPTER 2

LITERATURE REVIEW

Concussions are a very highly debated topic due to worry about the long-term deficits a concussion can have on an individual. Current guidelines recommend a multifaceted approach to concussion evaluation and management including symptom reporting, cognitive assessment, and balance assessments. Following concussion many patients will experience vestibular symptoms of dizziness and balance disorder. These clinical symptoms have been associated with prolonged recovery following concussion; however it is unclear how repetitive subconcussive head impacts may affect the balance/postural control.

Epidemiology

Concussions are a complex pathophysiological process caused by either direct or indirect biomechanical forces on the brain causing the individual to experience clinical symptoms. Subconcussive impacts are characterized by the mechanical transfer of energy from a blow to the brain that may cause neuronal or axonal injury, but the athlete does not exhibit any clinical symptoms.[8] In collegiate athletics, men's and women's ice hockey and men's wrestling have the highest risk of sustaining a concussion, however football had the highest overall number of concussions.[9] Concussion incidences in collegiate athletics have been consistently higher in football relative to other sports. After sustaining a concussion, most athletes recover within 7-14 days, however some athletes experience prolonged recovery.[10] Initial symptom forms has been associated with prolonged recovery, with dizziness and balance dysfunction being the most common.[10]

Following concussion, athletes are at a greater risk for sustaining another concussion within the first 7-10 days.[11] Additionally, concussed athletes and recovering athletes are at a greater risk for sustaining lower extremity injuries.[12] This may be due to vestibular system dysfunction, because gait and balance dysfunction may outlast common concussion symptoms.[13] A deficit in vestibular function will decrease the athlete's balance and spatial awareness, causing lack of control of their extremities. During athletic participation athletes must be able to process large amount of information very quickly, while maintaining postural control.

Vestibular Function

The vestibular system is major contributor to balance maintenance and spatial awareness. Goal-directed behaviors are always accompanied by automatic postural control that includes balance adjustment and muscle tone regulation.[14] Movement patterns in a healthy individual are generated through the spinal cord which is called central pattern generators.[14] During sport related activities, unanticipatory circumstances are often present that require compensatory movements to be made. Sensory information must be integrated by the central and peripheral nervous systems so that postural awareness and balance can be maintained to complete the task.

The vestibular system is composed of two parts; the central nervous system (brain) and the peripheral nervous system (inner ear), that work together to maintain spatial orientation and postural control.[15] The peripheral vestibular system is located within the inner ear and consists of a bony labyrinth and a membranous labyrinth.[16] Within the bony labyrinth consist the cochlea, the vestibule and the semicircular canals.[16] The three semicircular canals are positioned in the sagittal, frontal and transverse planes, that have otoliths inside of them that move freely, which are important in detecting angular rotation of the head.[17] The saccule and utricle, two otolithic structures, detect linear acceleration of the head.[17] The saccule senses motion in the vertical plane and the utricle senses motion in the horizontal plane.[16] Each of these types of vestibular receptors collect information regarding spatial movement, then relay information via neural impulses to the CNS, which allows for compensatory motor function that facilitates postural control.[17]

Vestibular receptors transmit signals to the brain when the head is accelerating in either an angular or linear direction.[18] Information from the vestibular receptors allows the musculature to maintain a solid base of support through postural stability. The vestibulocular reflex (VOR) stabilizes gaze when the head is in motion by providing neural feedback when the head is moving in a linear or angular direction.[18] The VOR allows the individual to maintain clear vision due to compensatory directional movement of the eye in regards to movement of the head.

The VOR works in conjunction with the vestibulospinal reflex (VSR) to maintain postural control of the body. The VSR activates postural musculature to allow for compensatory movements when the body is moving in space.[18] Muscle spindles are located within the muscle belly and provide feedback to the central nervous system by detecting change in length of the fibers. Muscle spindles a located in the cervical musculature to provide proprioceptive feedback to the brain via the VSR.[18] Together the VOR and VSR provide visual and proprioceptive feedback to the central nervous system that allows for a healthy individual to maintain postural control during both stationary and ambulatory activities.

Vestibular Function Following Concussion

Following sport-related concussion the athlete can experience a variety of symptoms; vestibular symptoms are not often addressed by the clinician and can cause dysfunction for the patient. Vestibular dysfunction can be identified as stemming from either the central vestibular system or the peripheral vestibular system.[19] Vestibular dysfunction following concussion is often present through symptoms of dizziness, nausea, vertigo, blurred vision or discomfort in busy environments that is high in stimuli.[20] Vestibular dysfunction and symptoms can be associated with worse outcomes in both the acute (less than 1 week) and subacute phase (1-3 weeks) following concussion.[21] There is evidence to suggest that about 10-30% of athletes that sustain a concussion experience prolonged recovery due to vestibular dysfunction.[22] When dizziness is present immediately following concussion the risk of delayed recovery that exceeds 21 days increases 6 fold, compared to patients that do not experience dizziness.[21] It is clear that patients experiencing vestibular dysfunction following concussion have an increased risk of experiencing delayed recovery. Outcome measures that identify which athletes are experiencing vestibular dysfunction must be used by clinicians, so that problem-based health care can be provided.

Patient Reported Outcome Measures

When evaluating balance/postural control in an athlete, clinicians can use patient-reported outcome measures, balance assessment and oculomotor assessment to identify the problems that are present. Self-reported outcome measures are used so that the clinician can get a representation of how the patient perceives the dysfunction they are experiencing. Patient reported outcomes can include Numeric Perceived Rating Scale (NPRS) of dizziness, the Dizziness Handicap Inventory (DHI), the Situational Vertigo Questionnaire (SVQ), and the Activities-Specific Balance Confidence (ABC) scale, which are subjective tests that the patient can relay to the clinician. The NPRS measures the patient's subjective level of dizziness on a scale of 0-100. The DHI is a questionnaire that consists of 25 questions, with 7 related to physical aspects, 9 related to emotional aspects and 9 related to functional aspects.[23] The SVQ is a 19 item questionnaire that is specifically aimed at identifying patients that are experiencing visual vertigo symptoms.[24] The ABC scale is a 16 item questionnaire designed for evaluating the risk of falls while completing everyday activities.[24] Each activity is rated by the patient from a 0-100, based on their confidence of completing the task. Patient reported outcome measures are important for clinicians to use so that a valid subjective representation can be made in regards to the patient's balance/postural control.

Balance Assessment

Objective measures are an important part of balance assessment because they provide both the clinician and patient with quantitative measures that can be compared over time. Balance can be assessed in different conditions that progress from simple to complex tasks, these tasks can be grouped into static, dynamic and functional.[17] A test that the clinician can perform is the Balance Error Scoring System (BESS), which can be performed by a clinician watching for balance errors by an athlete while balancing in 6 modified positions. The BESS test is a valid and reliable test for measuring postural stability, it can be performed on the sideline or in a laboratory setting.[25] The BESS test is a clinically feasible test but has a low interrater (0.57) and intrarater (0.74) reliability and sensitivity level of (0.34).[26] The BESS test is a very commonly used test to assess postural stability, but it may not be sensitive enough to detect the very subtle deficits that may be present following subconcussive impact.

The Sensory Organization Test (SOT) is a test that can be used to evaluate balance function; this test disrupts the somatosensory, visual and vestibular systems.

The SOT is a test that is comprised of 6 conditions that manipulates the surface the patients is standing on and the vision to determine balance assessment.[27] This computerized test has been shown to have very low levels of sensitivity (2-61.9%) and high levels of specificity (92.3-94.9%).[28] This test has also been combined with the subject completing cognitive tasks and has shown that balance is maintained at the expense of cognitive function in terms of reaction time and errors when performed at the same time.[27] During sport participation athletes constantly have to make decisions while maintaining postural control. The SOT shows that these two clinical measures are related and dependent when performing goal-oriented tasks.

Dysfunction of balance/postural control can result in gait abnormalities and postural instabilities that can be exacerbated by head turns, body turns and inaccurate sensory information from the peripheral vestibular system.[29] The Dynamic Gait Index (DGI) is a functional test that was developed to assess dynamic postural stability by completing 8 different tasks that vary in terms of walking speed, walking with head turns, moving over or around obstacles, ambulating stairs and making quick turns.[29] Gait assessments can be used to test vestibular function and can be measured by motion analysis or via time trials.[17] The DGI as of now has a moderate level of interrater reliability at 0.68 but could be improved by creating more objective grading criteria, standardized instructions regarding grading and administration of test, training scenarios and items that more accurately assess gait deficits seen in vestibular disorders.[29] These tests provide dynamic variability, which cause the vestibular system to react and maintain postural control of the body. If the athlete has decreased ability to perform the tasks that are required following head impact, the athlete may be experiencing balance/postural control deficits.

The Functional Gait Assessment (FGA) is an assessment of a patient's ability to maintain postural stability while ambulating through gait related tasks. The FGA is a test that comprises 7 out of 8 tasks that are present with the DGI, with the addition of 3 new items; 1) gait with a narrow base of support, 2) ambulating backwards, and 3) gait with eyes closed.[30] The new items were added to the test so that the individual would have to rely on vestibular and somatosensory input to maintain postural control while completing the task.[30] The intrarater reliability of the

FGA was 0.83 and the interrater reliability was 0.84.[31] The FGA is an add-on to the DGI to better target the specific balance/postural control deficits that a patient is experiencing. In an athletic population, the difficulty of the dynamic tests needs to be higher so as to challenge balance/postural control. Finding the optimal outcome measure to use when evaluating balance/postural control may be the key to detecting the deficits that may be present in athletes following cumulative subconcussive head impact.

Oculomotor Assessment

Oculomotor assessment is an important part of the clinical evaluation and should be performed in conjunction with the neurological assessment. These assessments can be used to rule out severe brain injury such as cranial nerve involvement.[17] This also helps to provide the clinician and athlete with an objective form of measure that can be later compared to over time. The King Devick test was developed to test oculomotor function by facilitating saccadic eye movement, attention and processing speed.[17] Oculomotor functional testing is important because it can help to determine whether or not an athlete can process the dynamic stimuli that are present in their sport. If oculomotor function is impaired in conjunction with the vestibular system, the athlete is at a greater risk for further injury.

Vestibular Treatment

In the past the recommended treatment for concussion was rest until the resolution of clinical symptoms, followed by a graded exertion protocol back to return to play. Following recent consensus statements, a more active approach is being utilized when managing concussions, which allows patients to begin sub threshold, low intensity exercise 24-48 hours post-concussion.[12] Vestibular rehabilitation has been included in this review because it has been shown to positively affect patients experiencing vestibular dysfunction.

If a patient has been experiencing concussion symptoms of balance disorder and dizziness, vestibular rehabilitation is an active rehabilitative technique that can benefit the patient. There are many different forms of vestibular rehabilitation that can be used, and should be chosen based on dysfunction present and the clinical symptoms that the patient is reporting. Most individuals with vestibular dysfunction will experience resolution of symptoms over time, however some patients will experience prolonged recovery that needs additional therapy. Vestibular rehabilitative therapy is a very loose term that encompasses many forms of therapy that aim to desensitize the vestibular system to movements or positions that facilitate symptoms felt by the athlete.[17] This type of therapy is typically used on patients experiencing chronic symptoms that have been occurring for up to 10-12 weeks and is beneficial to 60-70% of patients.[17]

Typical vestibular rehabilitation therapies include habituation exercises, substitution exercises, adaptation exercises and repositioning maneuvers. Habituation exercises are used to attempt to minimize sensitivity to stimuli by repeated exposure exercises until the symptoms resolve.[17] Substitution exercises try to minimize sensitivity to tasks by compensation of other components of the vestibular system to perform that task.[17] Adaptation exercises progress from simple to complex visual stimuli that assists the CNS to make long term adaptations to the loss of vestibular input.[17] Canalith repositioning maneuvers via a series if manipulations can be used to try to treat vestibular dysfunction that can be arising from otolithic organs being displaced within the semicircular canals.[17]

In the past, clinicians have recommended that an athlete with a concussion does not begin any physical activity until there is total resolution of symptoms, then the athlete can begin a graded progression back to return to play. The purpose of the progression back into physical activity is to try to prevent the reproduction of symptoms, and return to play of an athlete that may not be fully recovered from their concussion. Each step of the return to play progression is a total of 24 hours in duration, and the athlete must not experience symptoms during that time range to progress to the next stage the following day.

Head Impact Biomechanics

Within contact sports, biomechanical forces can be transmitted either directly or indirectly to the head, which can lead to concussion.[3] Contact forces occur when the head physically strikes an object or surface. Inertial loading or acceleration occurs due to impulsive head motion, where a blow to the body causes indirect transmission of acceleration to the head.[3] It is generally accepted that higher impact accelerations are associated with more severe injuries.[3] These impact accelerations can be broken down into linear and rotational acceleration. When evaluating head impact biomechanics it has been shown that 90% of the tissue damage to the brain occurs from the rotational forces, compared to 10% of the tissue damage due to linear forces placed on the brain.[32]

Rotational acceleration results in shear stress, which can cause tissue damage. Brain tissue is resistant to change when slow pressure is applied; however when rapid pressure is applied it causes an increased level of deformation of the brain tissue[3] Shear forces have been shown to produce higher level of tissue deformation in brain tissue, which is typically caused when rotational acceleration occurs.[3] Rapid change in rotational acceleration has also been shown to increase the likelihood of causing a concussive episode.[3] Head impacts occur very rapidly and often during participation in sport, understanding how the brain responds to stress is important for clinicians to understand so that the nature of the injury is clear.

Concussive Head Impacts

In the United States as many as 300,000 sport related concussions occur to athletes participating in sports annually, and in the year 2002-2003 8% of all injuries in collegiate football were concussions.[33] The sport of football has been reported to have a high likelihood of recurrent concussions which can lead to acute outcomes due to multiple injuries.[2] In the late 1980's performance of helmets and attention on the incidence of concussions began to occur in the general population as professional football players began to experience repeated concussion causing them to retire early.[34] Repeated concussion was causing retired players to experience concussive symptoms that were affecting their activities of daily living. These symptoms were characterized as immediate impairment or alteration of neural function that could be identified clinically by a medical professional.[34] Researchers began using accelerometers to try to assess biomechanics of head impacts to identify a threshold in which a concussion would occur in an athlete.[33]

Early stages of accelerometer research allowed for limited interpretation because there was no way of fixing an accelerometer to the head of a soccer player to obtain accurate data.[2] Pellman et al. used video recordings of NFL concussive episodes and reconstructed the incidence with crash test dummies to try to identify a quantifiable threshold in which concussions occurred. Pellman et al. found that the average concussion involved an impact velocity of 9.3m/s, head velocity change of 7.2m/s, head acceleration of 98g and duration of 15 milliseconds.[34] This study found that there was a strong correlation between concussion and linear acceleration following head impact.[34] Pellman et al. postulated that linear acceleration should be the main assessment determinant for helmet quality via protection.[34]

Duma et al. performed a study where spring accelerometers were placed in the helmets of Division I collegiate football players that measured real-time head accelerations and impact magnitudes.[33] That study came to the conclusion that the Head Impact Telemetry (HIT) System was effective at providing data for thousands of head impacts over the course of a season, that could be used in conjunction of other clinical evaluation techniques to help a medical professional identify an athlete who may have received a hit with enough force to sustain a concussion.[33]

Researchers have not been able to establish an exact threshold necessary for a concussion to occur.[2] The biomechanics of a concussion are not fully understood, however it is known that both linear and rotational head accelerations are major contributors to neurophysiological injury, and usually occur in combination.[2] Guskiewicz et al. surmises that an athlete that receives an impact that is greater than 90g via the HIT system, may not necessarily result in immediate symptoms that characterize a concussion.[2] Although helmet accelerometers hold promise for better understanding the biomechanics related to concussion, they cannot be used as a clinical tool for the diagnosis of concussion.

Impact location may also contribute to concussion risk due to the type of force and acceleration that can be placed on the head. Linear impacts that connect on the facemask, side of the helmet, or to the back of the helmet were often associated with concussion.[2] Guskiewicz et al. found that magnitude and location of impact had no relation between clinical outcomes of symptoms, balance or neuropsychological performance.[2] Therefore, magnitude and location of impact can most likely not be used as a predictor of athletes who can be diagnosed with a concussion.[2] There have been varying results found by researchers regarding impact location, meaning that impact location cannot provide reliable predictors on whether an athlete sustained a concussion.

Subconcussive Head Impacts

Subconcussive impacts are characterized by the mechanical transfer of energy from a blow to the brain that can cause neuronal or axonal injury, but without any clinical symptoms.[8] The literature has yet to conclusively create a definition of subconcussion that is recognizable across studies describing head impacts that do not result in concussion. Terms have been used to describe the head impact, such as subconcussive hit, subconcussive blow and subconcussive impact. Terms have also been used to describe the damage associated with the head impact that range from just subconcussion, to subconcussive injury and subconcussive trauma.[35] Subconcussive blows to the head have been shown to produce tearing of axons and formation of axonal retraction bulbs in motor pathways located within the brainstem.[5] Athletes who participate in football and other contact sports are exposed to repetitive subconcussive head impacts each day during either practice or competition.[36] Though subconcussive head impacts by definition do not result in concussion, repetitive head impact exposure has been associated with the risk of developing late-life neurodegenerative disease.[36]

The frequency of subconcussive head impacts in football is important due to the sheer number of impacts that occur due to the nature of the sport. Crisco et al. found that the median number of hits over the course of a collegiate football season was 420 and a maximum number of 2492.[5] This is a wide range in terms of frequency of impact that emphasizes the differences of frequency that can occur between members of the same team. Guskiewicz et al, may have found a better representation of the average number of subconcussive impacts that collegiate football players receive over the course of a season, at 950 total impacts without clinically observable symptoms.[2]

When observing subconcussive impacts in collegiate football players, cumulative subconcussive head impact frequency may differ based on player position, researchers have found some similar as well as varying results. Offense and defensive linemen have been shown to experience the highest amount of cumulative head impacts over the course of a single season.[7] Bailes et al. found that linebackers and lineman experienced the highest number of subconcussive head impacts, in addition to quarterbacks and running backs experiencing the highest magnitude of impacts over the course of a single season.[5] Gysland et al. found that there was no difference associated with magnitude of head impact based on position group over the course of a season.[7] Researchers have found similar results in terms of subconcussive head impact frequency across position group with slight variations, which may show that impact frequency is not fully understood regarding the sport of football at this time.

Subconcussive head impacts have been shown to cause neurophysiological changes that can be identified via advanced imaging techniques such as magnetic resonance imaging (MRI). Talvage et al. found high school football players who had no clinically observable symptoms that would warrant the diagnosis of a concussion had quantifiable neurophysiological deficits.[4] Due to the fact that these athletes did not have any clinically observable symptoms present they continued to participate in practices and games, receiving more subconcussive blows. This repeated level of subconcussive blows can increase their likelihood of experiencing neurodegeneration over their lifetime.[4] At this time it has not been conclusively determined whether or not subconcussive impacts are causing neurodegeneration.

Determining whether or not subconcussive impacts are causing long-term neurodegenerative changes may be related to identifying clinical outcome measure that are affected by subconcussive impacts. Clinical outcomes related to subconcussive impacts are difficult to identify in athletes because many tests may not be sensitive enough to detect the minor changes.[5] Killem et al. found that non-concussed collegiate athletes scored lower on memory tests than did collegiate athletes who did not participate in contact based sports.[5] McAllister et al, analyzed data from Division I football and ice hockey players and found that athletes that had high levels of head impact exposures had poorer post season cognitive scores.[5] Cognition and memory may be affected by cumulative subconcussive impacts over the course of a season. The literature has not found conclusive evidence that cognition is affected by subconcussive impact, this may be due to lack of sensitivity of tests for when the athlete is being tested following impact.

The SOT is a balance outcome measure that has been shown to be related to cognition when the patient is maintaining balance/postural control, in addition to performing cognitive tasks.[27] Determining whether balance deficits are caused by cumulative subconcussive impacts may provide valuable clinical tools for clinicians in the field. When evaluating collegiate football player impact exposures over the course of a season, Gysland et al. found pre-post season deficits in balance via the SOT.[7] When examining adults who participated in repeated soccer heading, similar results were found. These individuals performed soccer heading 10 times and then were evaluated while standing and during walking. Hwang et al. found a consistent deficit in vestibular processing while standing, immediately following subconcussive head impact, that returned back to normal within 24 hours.[6] The subjects were also tested while walking to determine if balance deficits were present during a more functional task. While walking an increase in medial to lateral trunk orientation displacement was observed in addition to velocity variability, that again returned to normal within 24 hours.[6] Short and long-term balance/postural control deficits have been shown to be present in athletes and may be associated with cumulative subconcussive impact.

During a practice or game, collision-based athletes can experience blows to the head that are of high and low velocity. A high velocity hit can cause the athlete to experience immediate dizziness, confusion and postural instability, which relates back to the function of the vestibular system.[6] A study was completed that took head impact data on collegiate football players who sustained high and low head impacts and evaluated how balance was affected. McCaffery et al. found that the athletes did not experience a decline in either balance or cognition after sustaining a head impact that was greater than 90g.[37] The athlete did not experience balance deficits with a single hit, but the accumulation of hits over the course of a season or a career may affect balance/postural control.[38] Clinicians may not be identifying clinically relevant differences because the tests that the clinician is using may not be sensitive enough to identify the change in postural control.[5]

Subconcussive impacts occur at varying ranges of force and exposure depending on a multitude of factors. Identifying specific categories of subconcussive impact may be beneficial for researchers and clinicians to make conclusive decisions on athletes to be tested for balance/postural control deficits. Mainwaring et al. stated that establishing levels of low, medium and high subconcussive exposure could help distinguish athletes who are at a higher risk of neurocognitive deficits.[35]

When an athlete is participating in sport related activities, balance and spatial awareness are very important in terms of safety and competitiveness. If an athlete's balance/postural control is partially compromised, there is an increased chance that they could receive a blow to the head causing a concussion and also an increased chance of injury to other body parts.[13] Identifying a clinical outcome measure that is sensitive enough to detect minor balance/postural control deficits could be the key to determining the effects of cumulative subconcussive impact. Outcome measures that involve dynamic movement such as the DGI or the FGA may provide a more realistic measurement of balance deficits in an athletic population.

CHAPTER 3

METHODS

Data sources and searches

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Guidelines were followed. Eleven databases were searched which included; CINAHL, Cochrane Central Register of Controlled Trials, Cochrane Database of Systematic Reviews, Conference Proceedings Citation Index, Embase, ERIC, Medline, Proquest Dissertation and Theses Global Database, PhychInfo, PubMed and SPORTDiscus. The search iteration, ((subconcuss* OR sub-concuss*) AND (sport* OR sports OR athlet* OR player*)) OR ((repetitive OR multiple OR reoccurr* OR recur* OR cumulative OR chronic) AND (brain OR head) AND (sport* OR sports OR athlet* OR player*)) OR ((vestibul* OR balanc* OR "spatial orientation" OR stability OR gait OR postur* OR oculomotor* OR oculo-motor*) AND (injury* OR impact* OR hit* OR hits OR hitting OR blow* OR trauma* OR traumas OR traumatic) AND (brain OR head) AND (sport* OR sports OR athlet* OR player*)), was used to identify articles that may be included in this systematic review. The databases searched, the number of results, and the number of duplicates removed are provided in **Table 4.1**.

Inclusion and Exclusion Criteria

Studies were limited to those using human subjects participating in athletics. All included studies were published in English. Exclusion criteria included: 1) non-peer reviewed articles, 2) studies not directly investigating subconcussive impacts (i.e., concussion and traumatic brain injury studies were excluded), 3) reviews or case studies, and 4) non-athletic related head impacts. Studies were limited to those that collected balance objective measures. To qualify objective vestibular measures, both static and dynamic balance/spatial awareness/postural control were evaluated by certified medical professionals following subconcussive impact.

Study Selection

The authors screened the title, abstracts, and full-texts that resulted from the literature search. First, the search terms yielded 26,117 studies imported into Covidence from the previously mentioned search engines. Next, duplicate articles (n=10,487) were removed. After removing duplicates, 15,630 articles were screened for title and abstract reading by two reviewers based on inclusion and exclusion criteria. Any disagreements were adjudicated by a third rater.

Assessing study quality

Three quality assessment tools were used to evaluate the quality of the studies: 1) the Downs and Black Checklist for Quality Appraisal (D&B), 2) the Scottish Intercollegiate Guidelines Network (SIGN) and 3) the Subconcussion-Specific Tool (SST). The Downs and Black Checklist is a 27-point quality appraisal tool that refers to the power of the study.[39] The Subconcussion Specific Tool is a quality appraisal tool that was created specifically for articles pertaining to subconcussions.[40] The Scottish Intercollegiate Guidelines Network is a grading system used to develop evidence based clinical guidelines in Scotland.[41] Articles that received a score of 3 or above were classified as Category A and articles that received a score of 2 or below were classified as Category B.

CHAPTER 4

MANUSCRIPT

Introduction

Sport-related concussions are a highly researched and debated topic that affects athletes in all sports at all levels. Concussions occur when biomechanical forces are transmitted to the brain via direct or indirect forces causing neurophysiological changes that can be observed via clinically relevant symptoms.[1] While concussive head impacts are concerning, most impacts sustained by athletes who participate in contact based sports are subconcussive. Collegiate football players can receive up to 950 subconcussive head impacts each season.[2] There is ambiguity in the current literature on specific short- and long-term effects of subconcussive impacts, particularly related to clinically relevant outcomes.

Previous research has not been able to establish an exact threshold at which concussions occur, due to brain dynamics during head impact being very difficult to understand.[2] Head impacts can cause translational or rotational acceleration, rapid change in rotational acceleration has also been shown to increase the likelihood of causing a concussive episode.[3] Subconcussive head impacts can cause quantifiable deformation in brain tissue, without the patient exhibiting any clinically observable symptoms that can be associated with a concussion.[4] Depending on the sport that you play and the position can determine the sheer magnitude and number of subconcussive impacts that you may receive over the course of a season.[5] Subconcussive impacts over time may affect the vestibular system and other central integration systems relying on somatosensory and visual input, which could cause balance/postural deficits in athletes.

The central nervous system detects and receives information from the peripheral nervous system so as to maintain balance and spatial awareness.[6] Tests such as the Sensory Organization Test (SOT) and the Balance Error Scoring System (BESS) sensory integration and it's effect on balance.[7] Whether or not the number of cumulative subconcussive impacts can cause balance/postural control deficits has yet to be determined. This may be due to the level of sensitivity of the balance tests that are currently used to assess balance/postural control in athletes. Researchers have not been able to determine the level of magnitude that a subconcussive impact needs to reach to cause neurophysiological damage to the brain. In order to make evidence-based clinical decisions, clinicians must first understand how subconcussive impacts affect balance overall. This will allow clinicians to provide the best evidence-based care to prevent long-term deterioration of balance deficits.

The purpose of this systematic review is to determine what is currently known regarding the effect of subconcussive head impacts on balance in athletes. A comprehensive understanding of balance deficits following head impact exposure will add to the growing body of literature surrounding the short- and long-term affects of subconcussive head impacts, and help improve sport safety and long-term health.

Methods

Data sources and searches

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Guidelines were followed. Eleven databases were searched which included; CINAHL, Cochrane Central Register of Controlled Trials, Cochrane Database of Systematic Reviews, Conference

Proceedings Citation Index, Embase, ERIC, Medline, Proquest Dissertation and Theses Global Database, PhychInfo, PubMed and SPORTDiscus. The search iteration, ((subconcuss* OR sub-concuss*) AND (sport* OR sports OR athlet* OR player*)) OR ((repetitive OR multiple OR reoccurr* OR recur* OR cumulative OR chronic) AND (brain OR head) AND (sport* OR sports OR athlet* OR player*)) OR ((vestibul* OR balanc* OR "spatial orientation" OR stability OR gait OR postur* OR oculomotor* OR oculo-motor*) AND (injury* OR impact* OR hit* OR hits OR hitting OR blow* OR trauma* OR traumas OR traumatic) AND (brain OR head) AND (sport* OR sports OR athlet* OR player*)), was used to identify articles that may be included in this systematic review. The databases searched, the number of results, and the number of duplicates removed are provided in **Table 4.1**.

Inclusion and Exclusion Criteria

Studies were limited to those using human subjects participating in athletics. All included studies were published in English. Exclusion criteria included: 1) non-peer reviewed articles and abstracts, 2) studies not directly investigating subconcussive impacts (i.e., concussion and traumatic brain injury studies were excluded), 3) reviews or case studies, and 4) non-athletic related head impacts. Studies were limited to those that collected balance objective measures. To qualify objective balance measures, both static and dynamic balance/spatial awareness/postural control were evaluated by certified medical professionals following subconcussive impact.

Study Selection

The authors screened the title, abstracts, and full-texts that resulted from the literature search. First, the search terms yielded 26,117 articles imported into Covidence from the previously mentioned search engines. Next, duplicate articles (n=10,487) were removed. After removing duplicates, 15,630 articles were screened for title and abstract reading by two reviewers based on inclusion and exclusion criteria. Any disagreements were adjudicated by a third rater.

Assessing study quality

Three quality assessment tools were used to evaluate the quality of the studies: 1) the Downs and Black Checklist for Quality Appraisal, 2) the Scottish Intercollegiate Guidelines Network (SIGN) and 3) the Subconcussion-Specific Tool. The Downs and Black Checklist is a 27-point quality appraisal tool that refers to the power of the study.[39] The Subconcussion Specific Tool is a quality appraisal tool that was created specifically for articles pertaining to subconcussive impacts[40] The Scottish Intercollegiate Guidelines Network is a grading system used to develop evidence based clinical guidelines in Scotland.[41] Articles that received a score of 3 or above were classified as Category A and articles that received a score of 2 or below were classified as Category B.

Results

Identifying studies

A total of 26,117 articles were identified via the electronic database search. Following the removal of duplicates, 15,630 studies were screened and 15,565 studies were deemed irrelevant. Sixty-five full-text studies were assessed for eligibility and 44 studies were excluded based on exclusion criteria. Twenty-one total studies were included for data extraction and were reviewed qualitatively (Prisma Diagram is provided in **Figure 4.1.**).

Data extraction and synthesis

An independent data extraction sheet was developed by the authors and the following data were extracted from each study: title, the setting where study was conducted, study design, sample size, sport(s) included, level of competition, mean age, sex, and the outcome measure(s) (See Table 4.2).

Study Characteristics

Study sample sizes ranged from 10 participants to 160 in this systematic review. In the systematic review there was 1 randomized prospective study, 1 double-blind repeated measures study, and 19 cohort studies. Males were the only sex analyzed in 9 studies, 2 studies included only females, and 10 studies analyzed both male and female participants. Football, lacrosse, soccer, hockey, rugby, women's volleyball and cheerleading were the sports included in the studies.

Quality and level of evidence

Methodological quality of the 21 studies was evaluated using 3 quality assessment tools. The studies had Downs and Black scores ranging from 13 to 21, with higher indicating better quality. Ten studies were classified as Category A, and 11 studies were classified as Category B using the Subconcussion-Specific Tool. Eighteen studies were given a level of evidence rating of a 2+ and three were designated 2- according to the SIGN. The quality review levels of each study are reported in Table 4.2.

Outcome measures

The most commonly used balance/postural control assessments for outcome measures within the included studies were the BESS test (9 studies), the NeuroCom (5 studies), and force plates (9 studies) measuring center of pressure and sway velocity. These outcome measures were reported because they were seen in multiple studies that showed differing results.

Acute vs. cumulative head impact exposure

The effect of subconcussive head impacts on balance/postural control was evaluated in studies after an acute bout of head impact exposure (n=7) and for a cumulative head impact exposure over a longer period of time (n=14), most commonly a competitive season. Articles evaluating acute head impact exposure demonstrate that there is no conclusive evidence that balance/postural control is affected in the short term. Three articles found postural deficits following head impact and four articles did not find any postural deficits. In addition, articles evaluating cumulative head impact exposure demonstrate that there is no conclusive evidence that balance/postural control is affected in the long term. Six articles found that postural control was affected by repetitive head impact exposure over the course of a season, and nine articles found that postural control was not affected.

Discussion

The purpose of this systematic review was to determine if the extant literature supported the hypothesis that subconcussive impacts cause balance/postural control deficits following head impact exposure (HIE). Review of several studies indicate there is no conclusive evidence that acute or cumulative HIE leads to balance/postural control deficits. The overall evidence is not conclusive, but some studies suggest force plates measured balance/postural control deficits following acute HIE and worse BESS test performance following cumulative HIE.

Acute Head Impact Exposure

All 7 studies assessing the effect of acute HIE on balance/postural control were completed with soccer athletes using a soccer heading protocol to elicit controlled subconcussive head impacts.[42–48] The number of headers that the participants were subjected to and the speed that the ball was traveling was not always consistent. Only two studies utilized the BESS test to assess balance/postural control following acute HIE.[43,47] In these studies, headers were performed over ten minute time increments, participants in one study performed five headers while in the other study each performed ten.[43,47] Participants were randomized into groups and received headers from the JUGS machine at 30, 40 or 50mph in one study, and all participants received headers at 25mph from the other.[43,47] One study had no significant differences in BESS score in any of the three groups with varying ball speed, while participants experienced deficits for 24 hours that returned to normal in the study that performed headers of 25mph out of the JUGS machine.[6,43] The foam and dome protocol, which is a very similar testing protocol to the BESS test, found no significant differences between six balance conditions, 1-3 on a firm surface, eyes open, eyes closed and with conflict dome, 4-6 were the same respectively but on an airex pad, for postural control following an acute bout of soccer heading.[48] The BESS test has been shown to have a learning effect which may be why balance/postural control deficits are not being seen following acute HIE.[49]

More advanced outcome measures including force plates, force plate treadmills, and the NeuroCom were used in the final four studies testing acute HIE. The MobileMat force plate and the virtual environment by NeuroCom detected postural deficits in collegiate, high school and youth soccer players but participants who were tested on the NeuroCom returned back to normal levels of balance/postural control with 24 hours.[42,44] The SOT and Accusway Force Plate did not detect any balance/postural deficits in collegiate soccer players.[45,46] Dynamic postural control was measured while the subject walked on a treadmill with force plates and no significant differences were found.[6] These highly sophisticated tests are sensitive to sway velocity and balance/postural control, which suggests that there are likely no meaningful balance/postural deficits following acute HIE.[45]

Sway velocity, measured by force plate or the NeuroCom, requires sensory integration from the visual and vestibular feedback loops, if sway velocity increases without other postural control impairments, soccer heading may be affecting overall sensory integration.[42] Dysfunction of the vestibular system creates a greater need to control the body's center of mass, which can lead to poorer postural control as sway velocity is increased. Both highly sophisticated tests such as force plates and the NeuroCom and less sophisticated tests such as the BESS test are finding similar results regarding balance/postural deficits and HIE, whether or not sway velocity is detected. Generally, there are no balance/postural control deficits following acute HIE and if there are, most resolve within 24 hours. This means that the BESS test may be a valid test for measure balance/postural deficits, especially for institutions with fewer resources.

As such, there is not conclusive evidence to support acute HIE leading to balance/postural deficits in athletes. If balance/postural deficits are present, they dissipate in short time frame. Limitations of these studies were that only soccer players were recruited, varying amounts of headers were performed, inconsistent use of outcome measures and in some cases small sample sizes. Until researchers can determine a more reliable testing protocol, and conclusive evidence is proposed, current medical care following acute HIE should not be altered.

Cumulative Head Impact Exposure

When assessing cumulative HIE a greater variety of sports were included compared to acute HIE. Cumulative HIE refers to athletes participating in a sport where they experience subconcussive head impacts and is a length of one season. Football, lacrosse, soccer, hockey, rugby and volleyball were sports that were included in studies assessing cumulative HIE. Studies involving cumulative HIE also included a greater range in age, two studies include adolescents in their sample population, which may have affected balance/postural control because they are still developing and becoming more proficient at their sport.[50,51]

Eight of the included studies assessing the effect of cumulative HIE on balance/postural control used the BESS test.[7,51–57] These studies varied in sport (soccer, football, lacrosse, volleyball), sport level (college, high school), and athlete sex. Among soccer athletes, Kaminski et al. found that collegiate female soccer players performed significantly worse on the post-season BESS test, compared to both college-aged controls not participating in any organized sport and high school soccer players.[55] The collegiate soccer players would have most likely participated in soccer for a longer duration of time (youth-college) than did the high school athletes and the controls. As shown with football players, longer duration of sport participation was associated with increased postural control deficits.[7] Increased cumulative repetitive head impact exposure may be another reason why the collegiate players showed increased postural control deficits than did the other groups enrolled in the study.[55]

Adversely, female soccer players (mean age = 19.4 yrs) demonstrated improved post-season BESS performance and no differences following a 90-day in-season window when compared to female volleyball athletes.[52] This overall improvement in BESS may be due to a practice effect that has been shown to occur after completing the test multiple times.[49] The lack of difference in BESS performance when compared to a non-collision sport group could illustrate that there are either no differences between contact and non-contact groups or that the BESS test is not sensitive enough to identify the postural control deficits.

Football and lacrosse athletes demonstrated post-season deficits in BESS performance with 32.4% (n=11) of lacrosse athletes increasing BESS errors by 7 or more, and 40.0% (n=18) of football athletes increasing BESS error by 3 or more.[57,58] Additionally among lacrosse athletes, a significant correlation was found between the total number of head impact exposures, as measured by GForce Trackers and the total number of errors on the foam surface.[58] The total time between testing sessions may have diminished the practice effect that is often noted with the BESS test allowing for more accurate results of postural control.[49] This means that the total number of errors that a patient makes on a foam surface may be sensitive enough to detect balance deficits following repetitive head impact.

In studies using the BESS test to assess balance and postural controls following cumulative HIE, post-season deficits were apparent in football, and lacrosse athletes though improvements were found in female soccer athletes.[52,57,58] Considering that the time from pre-season testing to post-season testing was much longer, the learning effect that may have been present during some of the acute HIE studies utilizing the BESS test, may have been negated. Research has shown that the BESS test is not significantly affected by sex.[59,60] However, Zimmer et al. found that women's soccer players perform better on the BESS test than do football and lacrosse players.[59] Some deficits were found among sports with a higher number of cumulative head impacts, this may indicate that high impact sports are at a greater risk of developing balance/postural control deficits.

Studies using more advanced balance/postural controls assessments to measure the effects of cumulative HIE generally found that deficits are not present.[37,51,54,61–63] Gysland et al. found that a greater history of lifetime football participation significantly predicted worse SOT performance from pre- to post-season in collegiate football athletes, and that SOT performance was impaired following a single season.[7] Incorporating number of years of playing experience could be a way to identify athletes who may be at a greater risk for long-term deficits from subconcussive impacts. Subsequent years participating in a contact sport could cause small balance/postural deficits to occur. Tracking how balance/postural control changes year to year to see if deficits are regained prior to the next season would be a future direction that researchers could study.

Force plates are often used by researchers to measure balance control in a stationary setting. Overall, balance/postural control deficits were not found following cumulative HIE when using force plates.[51,54,61–63] The experimental protocols used with force plate assessments primarily tested the athletes in a static position, which does not cause high levels of vestibular disruption. Murray et al. was the only study that tracked HIE using accelerometers instrumented in the athletes helmets.[63] If force plates could be used and also make the testing protocol more advanced and challenging for the participants, balance/postural control deficits may be able to be seen following cumulative HIE.

Myashita et al. performed a study including 33 division 1 men's lacrosse players which assessed balance over the course of a season.[56] Balance was assessed via the Stability Evaluation Test (SET) using a force plate, and performed all 6 conditions of the BESS test. During the season all players wore GForce Trackers in their helmets to track head impact exposure. Balance assessments revealed a significant increase in sway velocity for the double leg stance (firm surface), the tandem stance (firm surface), and the double leg (foam surface).[56] The only significant correlation between head impact data and sway velocity was shown on the tandem stance on a firm surface.[56] This suggests that sway velocity changes in the tandem stance may be sensitive to subconcussive impacts in athletes over the course of a competitive season.[56]

When evaluating balance/postural control using force plates in adolescent athletes there are more factors to consider. Among studies investigating youth football athletes, pre- to post-season balance/postural control deficits were either not found or balance/postural control improved.[51,62] This may be due to overall development of the young athletes, as they are training and becoming more proficient at their sport. Additionally, cumulative HIE over many years of sport participation may be more of a predictor of balance/postural control deficits, and therefore deficits are not yet evident in this younger population.

Dynamic balance assessments may be able detect postural deficits while providing an outcome measure that more closely mimics what the athletes are asked to perform during a sport activity. Three included studies assessed dynamic balance using the Lower Quarter Y-Balance test (YBT-LQ), the GAITRite, and the tandem gait test. Of these, only the YBT-LQ detected decreased dynamic balance control. The GAITRite, a portable walkway force plate analysis unit had no significant relationships between head impact kinematics in any single task or dual task gait performance.[61] The tandem gait test, used with football and soccer athletes, had an increase in average time of completion of the tandem gait test over the course of the season for the football players but it was not deemed significant.[53]

Conclusion

Overall, this review sought to consolidate and evaluate the effect of subconcussive impacts on balance/postural control. The review categorized head impact exposure metrics into acute and cumulative timelines. Insufficient evidence was presented to conclusively associate balance/postural control deficits following acute or cumulative head impact exposure. It may be that balance/postural control outcome measures are not sensitive enough to consistently identify deficits when they are present.

Given the evidence that was reviewed we conclude the following: 1) Balance/postural deficits are not seen following acute HIE but may be apparent following single-season exposure in collision, 2) generally low budget tests such as the BESS are similar to tests with advanced metrics, which is beneficial for clinicians who do not have the resources necessary for force plates and 3) consistent experimental protocols should be developed based on each balance/postural control outcome measure to allow for greater generalizability of results. Future research should be conducted to conclusively identify if balance/postural control deficits are present following subconcussive impact and the implications regarding the athlete's long-term health.

Table 4.1. Search strategy and results of the systematic literature search, with total number of unique articles per database.

Database	Records found	Duplicates removed
CINAHL (1985 to present)	1,257	875
Cochrane Central Register of Controlled Trials	206	89
Cochrane Database of Systematic Reviews	2	1
Conference Proceedings Citation Index (via Web of Science)	219	80
Embase (1970 to present)	10,184	4280
ERIC (1973 to present)	53	20
Medline	3,179	3121
Proquest Dissertation & Theses Global Database	475	37
PsychInfo (1969 to present)	1,577	993
PubMed	7,206	282
SPORTDiscus (1972 to present)	1,759	962
Total	26,117	10,740

Table 4.2. Characteristics and Quality Review of Included Studies.

Title	Setting	Study Design	Sample Size	Sport	Level	Mean Age (yrs)	Sex % Male	Outcome Measures	D&B[39]*	SST[35]†	SIGN[3]‡
Seasonal Changes in Functional Fitness and Neurocognitive Assessments in Youth Ice Hockey Players	Canada	Cohort	N/A	Hockey	Youth	8.9± 1.1	100%	Lower Quarter Y-Balance Test, Functional Movement Screen	17	2	2-
Repetitive head Impacts in Football Do Not Impair Dynamic Postural Control	USA	Cohort	47	Football and Cheer	Division 1	Football: 20.2± 1.2 Cheer: 19.8+-1.2	76%	Gait Performance via: Gait Rite (Gait Initiation, Gait and Gait Termination)	19	3	2+
Balance Error Scoring System Performance Changes After a Competitive Athletic Season	USA	Prospective Longitudinal Cohort	58	Women's Soccer, Women's Volleyball & Control	Division 1	WSOC: 19.4±1.6 WVB: 19.3±1.3 Control: 21.9±1.8	0%	BESS	20	2	2+
Postural Control Deficits After Repetitive Soccer Heading	USA	Cohort	160	Soccer & Control	College, High School and Youth	12-24	45%	MobileMat: Postural Control Assessment	19	4	2+

Effects of Repetitive Head Impacts on a Concussion Assessment Battery	USA	Prospective Longitudinal Cohort	38	Football (15) & Women's Soccer (23)	Division 1	FB: 19.5± 1 WSOC: 19.7±1.2	39%	SAC, BESS, King-Devick, Clinical Reaction Time, & ImPACT	19	4	2+
Subconcussive trauma, acute concussion, and history of multiple concussions: Effects on quiet stance postural control stability	Canada	Cohort	135	Football, Hockey and Rugby	Local Elite Junior	FB: 19.54± 1.49 Hockey: 18.48± 1.04 Rugby: 21.33± 2.07	100%	Force Plate, mBESS, SCAT3, SAC	15	3	2+
Effect of soccer heading ball speed on S100B, sideline concussion assessments and head impact kinematics	USA	Cohort	16	Soccer	Division 1	20.44	62%	SCAT2, mBESS, King-Devick Test	20	2	2+
The Relationship Between Subconcussive Impacts and Concussion History on Clinical Measures of Neurologic	USA	Cohort	46	Football	Division 1	19.65± 1.16	100%	Automated Neuropsychological Assessment Metrics, SAC, SOT, BESS, GSC	21	3	2+

Function in Collegiate Football Players											
Acute Changes in Postural Control after Soccer Heading	USA	Cohort	16	Soccer	College or Club athletes	21.2± 2	75%	NeuroCom	19	2	2+
Purposeful heading during a season does not influence cognitive function or balance in female soccer players	USA	Cohort	71	Soccer	Division 1, high school and junior varsity	18.5	0%	mBESS, Weshsler Digit Span Test, Hopkins Verbal Learning Test	21	2	2+
Analysis of Postural Stability in Collegiate Soccer players Before and After an Acute Bout of Heading Multiple Soccer Balls	USA	Cohort	10	Soccer	Division 1	21.4	80%	SOT	17	2	2-
Correlation of Head Impacts to change in Balance Error Scoring System Scores in Division 1	USA	Prospective Longitudinal Cohort	34	Lacrosse	Division 1	19.54± 1.42	100%	BESS	20	3	2+

Men's Lacrosse Players											
Prevalence of Neurocognitive and Balance Deficits in Collegiate Football Players Without Clinically Diagnosed Concussion	USA	Prospective Cohort	45	Football	Division 1	19.56±1.23	100%	ImPACT, BESS & Post-Concussion Symptom Scale	21	1	2+
Effects of Youth Football on Selected Clinical Measures of Neurologic Function: A Pilot Study	USA	Prospective Cohort	15	Football	Youth	13.4± 0.7	100%	AMTI Strain Gauge Force Platform, King Devick Test, ImPACT, Symptom Checklist	21	1	2-
Repetitive head impacts do not affect postural control following+A 17:I23 a competitive athletic season	USA	Prospective Cohort	28	Football and Non-Contact Cheer	Division 1	20.40± 1.12	60%	Force Plate Center of Pressure testing	20	2	2+
Effect of an acute bout of soccer heading on Postural Control and	USA	Randomized Prospective	31	Soccer	College Club teams	M: 20.7± 2.5 F: 19.4± 1.4	48%	Accusway force plate, Center of Pressure area and Velocity were measured, GSC	21	3	2+

Self-Reported Concussion Symptoms											
Measurement of Head Impacts in Collegiate Football Players: Clinical Measures of Concussion after High and Low-Magnitude Impacts	USA	Double Blind Repeated Measures Study	43	Football	Division 1	20.74± 1.62	100%	SOT, Automated Neuropsychological Assessment Metrics (ANAM), GSC	22	3	2+
Vestibular Dysfunction after Subconcussive Head Impact	USA	Prospective Cohort	20	Soccer	College, Intramural or Club	EXP: 20.7± 1.1 CON: 18.9± 1.1	75%	Galvanic Vestibular Stimulation (GVS), Walking Posture Control Assessment	20	2	2+
Postural Control and Head Impact Exposure in Youth Football Players: Comparison of the Balance Error Scoring System and a Force Plate Protocol	USA	Prospective Cohort	31	Football	Youth	9.9± 0.6	100%	BESS, IsoBALANCE measuring Center of Pressure	19	0	2+
No acute changes in postural control after	USA	Prospective Cohort	40	Soccer	College	19.45± 1.24	45%	Kistler type 9286A Force Platform and the "Foam and	22	3	2+

soccer heading								Dome Protocol"			
The role of subconcussive impacts on sway velocities in Division 1 men's lacrosse players	USA	Prospective Cohort	33	Lacrosse	Division 1	19.51± 1.2	100%	VSR Sport System (NeuroCom) took Stability Evaluation Test (SET)	19	3	2+

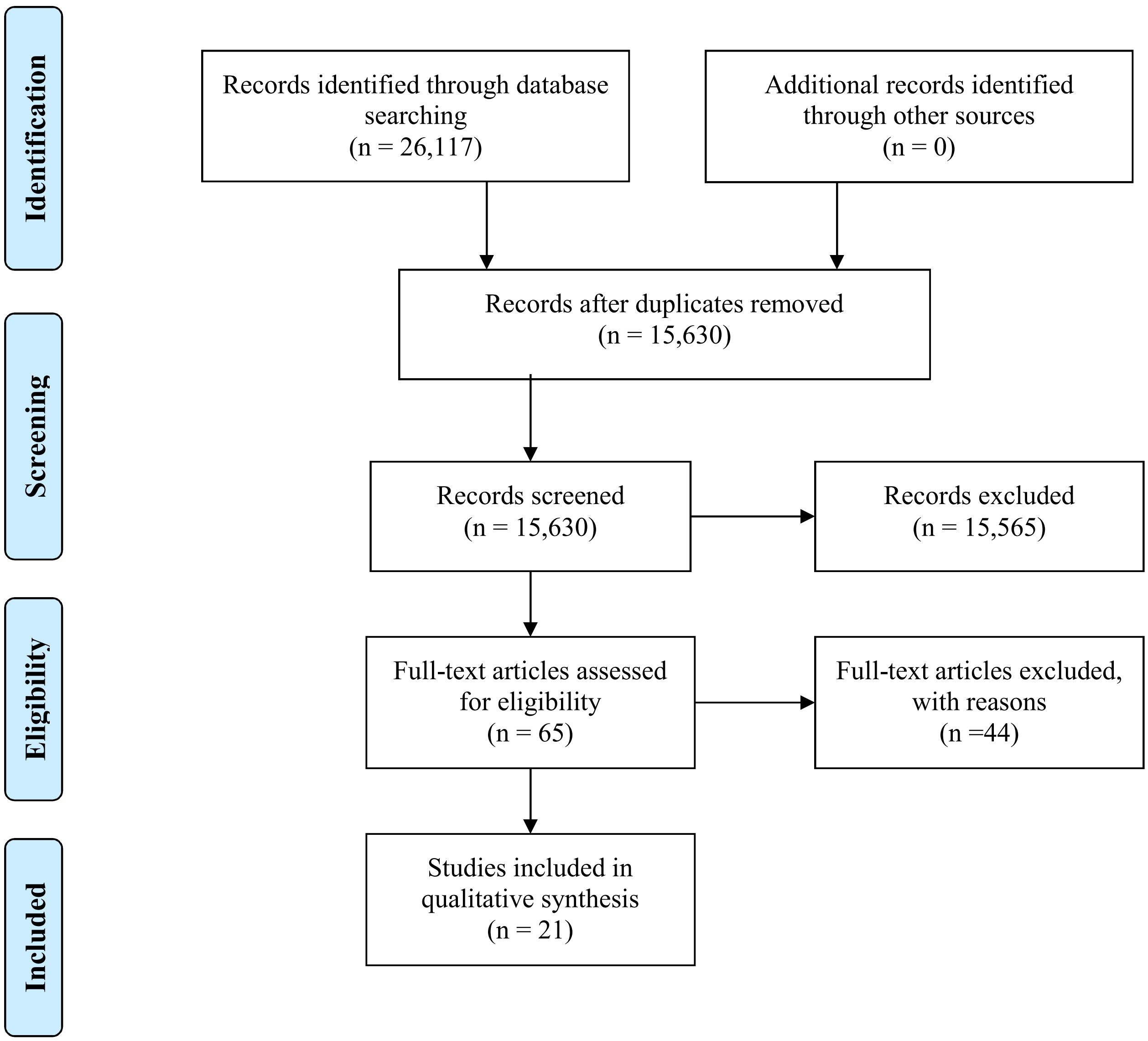
* Downs and Black Checklist for Quality Appraisal (D&B) is a 26-point checklist with a possible total score of 27, higher scores indicate a higher quality article.

† Subconcussion Specific Tool (SST) is a 5-point quality review resource used to determine if an article includes information that specifically pertains to subconcussive head impacts, higher scores indicate higher quality of articles with 5 being the highest score.

‡ The Scottish Intercollegiate Guidelines Network (SIGN) is a tool used to determine the level of evidence of a study based on the type of study design, lower scores indicate better higher levels of evidence with 1 being the highest and 5 being the lowest.

Figure 4.1. PRISMA flow diagram

Do Subconcussive Impacts cause Balance Deficits in Athletes?



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